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Evaluation of the Digital Opacity Compliance System in High Mountain Desert Environments

Final Report

Michael J. McFarland and Spencer H. Terry

University of Utah
302 Park Building
Salt Lake City, UT 84112

Daniel A. Stone and Steven L Rasmussen

Environmental Management Directorate
7274 Wardleigh Road
Hill Air Force Base, UT 84056

Michael J. Calidonna

Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403

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MATERIALS & MANUFACTURING DIRECTORATE
AIRBASE TECHNOLOGIES DIVISION
139 BARNES DRIVE, STE 2
TYNDALL AFB FL 32403-5323**

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Michael J. McFarland and Spencer H. Terry

Department of Civil and Environmental Engineering, Utah State University, Logan, Utah

Daniel A. Stone and Steven L. Rasmussen

Environmental Management Directorate, Hill Air Force Base, Ogden, Utah

Michael J. Calidonna

Engineering and Services Research Laboratory, Tyndall Air Force Base, Panama City, Florida

ABSTRACT

The digital opacity compliance system (DOCS) has been proposed as an alternative to the U.S. Environmental Protection Agency Reference Method 9 (Visual Determination of the Opacity of Emissions for Stationary Sources). The DOCS, which employs standard digital photography to estimate the opacity of visible emissions, was evaluated in a high mountain desert environment located in Weber County, UT. The DOCS recorded an average opacity deviation of 5.28% when applied to black smoke plumes having true opacities in the range of 0–100%, an error rate that was found to be significantly less than 7.5% (allowable error rate for attaining certification under Method 9). In contrast, results from estimating the opacity of white smoke plumes indicated that the accuracy of the DOCS was less than the Method 9 error rate only in the opacity range of 0–60%, over which the DOCS average opacity deviation was determined to be 6.7%. For the 0–40% opacity range, the DOCS recorded an average opacity deviation of 5.44% and 5.9% for black and white plumes, respectively.

IMPLICATIONS

Historically, Method 9 has been the preferred enforcement approach for verifying compliance with federal visible opacity standards because it is flexible and inexpensive relative to the costs associated with the purchase and operation of a continuous opacity monitor. The DOCS, which is an innovative technology that employs digital photography for quantifying visible opacity, has been proposed as an alternative to Method 9. The DOCS not only exhibits comparable performance flexibility, but it is also economically competitive and, under conditions of regulatory concern (i.e., 0–40% visible opacity), generates opacity measurements that are at least as accurate as those from Method 9.

Results from the present study suggest that the DOCS has the potential to quantify visible opacity with an error rate that is significantly less than the Method 9 permissible error rate. Although encouraging, it is unclear to what extent the DOCS is affected by climatic conditions other than those encountered in a dry desert environment. Future studies should focus on evaluating the performance of the DOCS under variable weather conditions.

INTRODUCTION

The presence of visible air emissions from industrial operations provides irrefutable evidence that airborne particles are being discharged into the atmosphere. Not only has the public expressed its concern regarding the negative psychological effects of visible emissions, but, under many circumstances, particulate emissions have been identified as the cause of increased human health and environmental risk.¹ Because of public concerns regarding the potential health and environmental impacts associated with visible air emissions, current federal statutes as well as many state and local air quality control laws currently regulate the opacity of plumes (i.e., point sources of air pollution) as well as fugitive particulate emissions. Opacity is defined as the percentage of light that is attenuated by airborne emissions. In other words, an opacity value of 20% indicates that 20% of the incident light is absorbed, scattered, or otherwise blocked by the plume while 80% is transmitted.² In many cases, the U.S. Environmental Protection Agency (EPA) and state regulatory authorities employ opacity estimates as a surrogate measure to verify particulate mass emission rate compliance. Typically, a regulated source will have two applicable particulate matter (PM) limits, one that specifies a maximum allowable mass emission rate (e.g., 20 lb of PM/hr) and another that specifies a maximum acceptable opacity (e.g., 30%). Although the goal of the federal opacity limits

is to reduce particulate emissions, EPA reserves the right to take enforcement action against any regulated source that violates its opacity standards regardless of the source's mass emission rate. The federal opacity standards for emissions from various industries are found in 40 CFR Part 60 (Standards of Performance for New and Modified Stationary Sources) and 40 CFR Parts 61 and 63 (Emission Standards for Hazardous Air Pollutants).³

Although EPA requires many regulated sources to install continuous opacity monitors in their air emission stacks, the primary method for determining compliance with federal opacity standards is EPA Reference Method 9. Method 9 relies on the ability of trained human observers to visually estimate the opacity of a plume by taking a series of opacity measurements at the rate of one every 15 sec for a specified period of time (typically 6–60 min).^{2,4,5} The collective set of opacity measurements is then averaged to develop a single opacity reading for the regulated source, which is subsequently compared against permitted levels. To qualify as a Method 9–certified visual observer, an individual must attend and successfully complete an EPA-approved Method 9 visual opacity “smoke school” once every six months. Successful completion of an EPA-approved Method 9 smoke school requires that the candidate enroll in both classroom and field training as well as receive a passing grade on an opacity field test. To achieve a passing grade on the opacity field test, the candidate must demonstrate the ability to assign an opacity reading to each of 25 white and 25 black smoke plumes with a margin of error not to exceed 7.5%.⁶

Advantages claimed for employing Method 9 to quantify visible opacity have included the fact that the approach (1) is relatively inexpensive, that is, compared with the cost of purchasing and maintaining a transmissometer or similar device, and (2) facilitates enforcement by allowing a regulator to take compliance measurements from outside the facility's property line. Although the courts have generally upheld the validity of Method 9 for compliance demonstration and enforcement, it is also a well-known fact that the use of human observers to quantify visible emissions is inherently subjective, a characteristic that exposes the Method 9 results to charges of imprecision, bias, and outright fraud. Moreover, with increasing public pressure to reduce airborne PM, regulators will continue to impose greater and more comprehensive limits to visible emissions, which will require, among other things, a commensurate increase in both the accuracy and reproducibility of the methods employed to verify the level of visible opacity.⁷

The current field study was designed to evaluate the technical performance of the Digital Opacity Compliance System (DOCS) at an EPA-approved smoke school conducted in a high mountain desert environment. The DOCS

uses a commercial off-the-shelf (COTS) digital camera to capture images of visible opacity, which are then downloaded to a standard personal computer and analyzed using proprietary commercially available software.⁸ Technological and economic advantages claimed by the developers of the DOCS over Method 9 have included (1) minimization of human bias associated with estimates of visible opacity, (2) creation of a permanent record of visible emissions for addressing compliance demonstration requirements and possible legal challenges, and (3) reduction in the annual air compliance costs for an affected facility.

BACKGROUND

In the DOCS, digital photographs of visible emissions are taken from valid positions according to Method 9 specifications. Once downloaded to a computer on which the DOCS proprietary software has been installed, the digital images can be evaluated for opacity. The initial steps in analyzing the digital image for opacity include (1) activating the DOCS proprietary opacity program, (2) electronically retrieving those digital photographs that are to be evaluated, and (3) using the DOCS proprietary software to draw an analysis box (or grid) around that portion of the visible emissions that will be analyzed (Figure 1).

After selection of the analysis box, the DOCS software utilizes standard statistical data analysis techniques for image processing to differentiate the visible emissions from the background.⁹ Once the visible emissions image data have been effectively separated from the digital background information, the software is capable of estimating visible opacity. Under normal circumstances, the user of the DOCS software rarely needs to understand the complex mathematical relationships associated with digital image processing techniques. Rather, the DOCS software user simply draws the analysis box around the area of the visible emissions to be analyzed and the software completes the opacity analysis.⁸

EXPERIMENTAL METHODS

To document the ability of the DOCS to accurately quantify visible opacity in a high mountain desert climate, the DOCS was evaluated at an EPA-approved Method 9

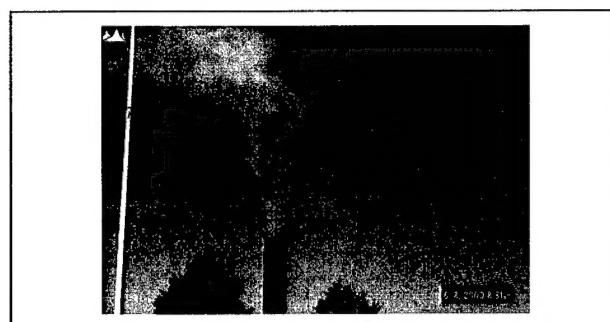


Figure 1. The analysis box drawn around the visible emissions.

certification smoke school conducted in Weber County, UT. The field tests were conducted October 2–4, 2001. The Weber County test site has a reported elevation of 4790 ft above sea level with geographic coordinates of approximately 41° 07' N (latitude) and 111° 58' W (longitude). The range of climatic data recorded over the three days of the DOCS testing included the following parameters: (1) mean air temperature, (2) average wind speed, (3) maximum wind speed, (4) wind direction, (5) sky conditions, (6) relative humidity, (7) visibility, (8) barometric pressure, (9) precipitation, (10) horizontal sun angle, and (11) vertical sun angle. Methods used to estimate the value of each climatic parameter are summarized in Table 1.

Field Activities

During the DOCS evaluation, four COTS digital cameras (Kodak DC290 or Kodak DC265) were employed to photograph visible emissions generated during the EPA-approved Method 9 certification field test. The DOCS commercial software was installed and tested on each of the cameras before any photographs were taken. No technical adjustments or physical modifications of the cameras were necessary to operate the DOCS camera software.

Each camera was positioned on a tripod to provide a clear view of the visible emissions. The minimum distance of the cameras from the stack was equivalent to at least three stack heights with the sun oriented in the 140° sector to the back of the camera/observer. Because the emissions stack used in the EPA-approved smoke school was approximately 15 ft high, DOCS cameras and visual observers were required to take visual opacity measurements at a distance of no less than 50 ft from the smoke

stack. Two cameras were placed directly in line between the sun and the smoke stack while each of the two remaining cameras was placed at the farthest allowable azimuth angle (Figure 2). Verification of the horizontal sun angle was established using a standard magnetic compass and Abney level device (Eastern Technical Associates, Inc.). These field procedures were adopted to be consistent with the published requirements for valid Method 9 visible emissions opacity measurements.^{4,5}

Digital photographs taken during each day of the DOCS testing were collected on a 128-Mb memory card. Following completion of each day of testing, the used memory cards were removed from the cameras, placed in a labeled container, and stored in a secure location. Digital photographs from the used memory cards were downloaded daily to a laptop computer for subsequent opacity measurement.

In addition to the four digital cameras used during the DOCS evaluation, an EPA-certified Method 9 smoke reader (i.e., human observer) was assigned to each camera location to read plume opacities during the first day of DOCS testing. The objective of assigning a limited number of EPA-certified Method 9 human observers to estimate plume opacity was to develop a preliminary comparison of the relative accuracy of certified human observers to the DOCS. Unlike the EPA Method 9 certification field-testing procedures, the certified human observers were not provided an opportunity to calibrate their vision before estimating plume opacity.⁵ The EPA-approved smoke generator that was used during the subsequent Method 9 certification field test was initially employed in the one-day certified human observer/DOCS side-by-side evaluation.

Opacity Determination Using the DOCS

After completion of field data collection activities, the opacity of each smoke plume captured as a digital image at the Weber County smoke school was estimated using the DOCS proprietary software by an independent eight-member panel that consisted of federal government civilian personnel, U.S. military personnel, and federal government contractors. Each panel member was provided a compact disc that contained all the digital photographs taken from the Weber County smoke school as well as the DOCS proprietary software and user guide. The panel members were required to work independently to estimate the plume opacity of each digital photograph using the furnished software. Once panel members had completed their analysis, the opacity results were transferred and stored electronically in a relational database for subsequent statistical evaluation. An independent quality control officer was assigned the responsibility of maintaining the integrity of all opacity data including the opacity results generated from the EPA-certified transmissometer

Table 1. Methods used to estimate the value of various climatic parameters.

Parameter	Method
Mean temperature	Standard liquid thermometer (Easter Technical Associates, Inc.)
Average wind speed	Standard anemometer (Easter Technical Associates, Inc.)
Max wind speed	National Weather Service (National Oceanic and Atmospheric Administration)
Wind direction	Standard anemometer (Easter Technical Associates, Inc.)
Sky conditions	Visual observation
Relative humidity	Sling psychrometer (Easter Technical Associates, Inc.)
Visibility	National Weather Service (National Oceanic and Atmospheric Administration)
Barometric pressure	National Weather Service (National Oceanic and Atmospheric Administration)
Precipitation	National Weather Service (National Oceanic and Atmospheric Administration)
Horizontal sun angle	Magnetic compass (Easter Technical Associates, Inc.)
Vertical sun angle	Abney level (Easter Technical Associates, Inc.)

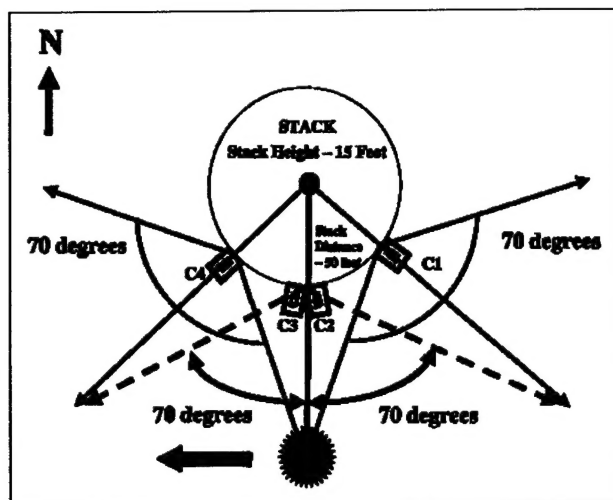


Figure 2. Positioning of the digital cameras (C1, C2, C3, and C4) and visual observers during the DOCS field study.

against which the DOCS and human observer opacity data were compared.

Evaluation of the DOCS to accurately measure visible opacity was based on comparing the opacity measurements of black and white smoke plumes reported by the eight-member DOCS panel to those recorded by the EPA-certified in-line transmissometer. Under these test conditions, those opacity levels recorded by the transmissometer were assumed to reflect the "true" (i.e., actual) visible opacity.

Statistical Evaluation of the DOCS Field Data

In evaluating the DOCS as a technically defensible alternative to Method 9 for estimating visible opacity, the absolute value of the average opacity deviation (i.e., differences in opacity readings recorded by the DOCS and the EPA-approved transmissometer) for both black and white smoke plumes was computed and compared with the Method 9 error rate of 7.5%.^{2,5} Moreover, to ensure that technological decisions resulting from the field data could be supported with a known degree of confidence, the uncertainty associated with the opacity deviation measurement was quantified by computing its 99% confidence interval. Equations 1–4 were employed to estimate the average opacity deviation and its 99% confidence interval.

Average opacity deviation

$$\bar{d} = \frac{\sum_{i=1}^n d_i}{n} = \frac{1}{n} \cdot \sum_{i=1}^n (Y_{1,i} - Y_{2,i}) \quad (1)$$

$$\text{Sample variance} = S_d^2 = \frac{\sum_{i=1}^n (d_i - \bar{d})^2}{n - 1} \quad (2)$$

$$\text{Standard error} = S_d = \frac{S_d}{\sqrt{n}} \quad (3)$$

$$99\% \text{ confidence interval} = \bar{d} \pm S_d \cdot t_{(\alpha/2), n-1} \quad (4)$$

where d_i is opacity deviation for each paired observation, n is number of paired observations, $Y_{1,i}$ is the i th opacity level as measured by the DOCS, $Y_{2,i}$ is the i th opacity level as measured by the EPA-certified transmissometer, α is level of significance (0.01 for the 99% confidence interval), $n - 1$ is degrees of freedom, and $t_{\alpha/2, n-1}$ is value of t statistic obtained from standard t -distribution tables (note for $n - 1 > 120$, $t_{0.01/2, n-1}$ is 2.326).

RESULTS

Weather conditions during the 3-day test period were near ideal for quantifying visible opacity. The climate was basically characterized by light winds, clear blue skies, and no precipitation.¹⁰ The values of the various climatic parameters monitored during the field test period are summarized in Table 2.

During the Weber County smoke school test, the DOCS photograph readers performed 6928 opacity estimates from digital photographs of plumes. Of those, only 4767 were deemed valid (2357 opacity estimates of black plumes and 2410 opacity estimates of white plumes). The decision to exclude 2161 opacity estimates from the DOCS statistical analyses was based on a number of technical problems, including (1) physical obstruction of the smoke plume (e.g., trees, clouds, telephone poles); (2) folding, twisting, or other significant physical disruptions to the plume; and (3) modification of digital image through use of the "brush" function in the DOCS software.⁸

The DOCS "brush" function is a capability the DOCS developers added to the software that allows the technology

Table 2. Climatic parameters measured or reported during the DOCS field tests.

	Day of Test		
	Day 1	Day 2	Day 3
Mean temperature (°F)	66.2	60.8	60.8
Average wind speed (mph)	8.9	9.7	8.1
Max wind speed (mph)	13.8	16.1	11.4
Wind direction ^a	NNW	ESE	SSE
Sky conditions	Clear	Clear	Clear
Relative humidity (%)	27.2	45.2	30.5
Visibility (mi)	7	7	7
Barometric pressure (in. Hg)	30.08	30.11	30.01
Precipitation (in.)	0	0	0
Vertical sun angle (°)	42.2	39.4	38.5

^aNNW = north by northwest, ESE = east by southeast, SSE = south by southeast.

user to digitally capture a part of the background of a valid photograph and utilize it to enhance the contrast of a plume (in other words, the software user can effectively brush in the background based on a particular sky condition found within the photograph). Although the DOCS photograph readers were initially allowed to utilize the "brush" function if they determined it could improve their ability to evaluate plume opacity, it was later determined that its use could potentially result in introducing bias into the statistical evaluation. Therefore, it was decided that all DOCS analyses that had been performed using the brush function would be deemed invalid and would not be included in the statistical analyses.

Quantitative Analysis

Table 3 summarizes the statistical results from the Weber County smoke school DOCS evaluation. The large difference in the number of readings recorded by the DOCS relative to the number reported by certified human observers was because one digital photograph could be evaluated by as many as eight DOCS photograph readers (i.e., number of members on the digital image evaluation panel), while the certified human observer only provided one opacity reading per smoke plume.

Over the full range of opacity (i.e., 0–100%), the average opacity deviation of the DOCS for black smoke was estimated to be 6.58% with a 99% confidence interval that ranged from 6.1 to 7. These results demonstrate that, for black smoke, the DOCS had a margin of error in measuring plume opacity that was significantly less than the acceptable error rate associated with Method 9 (i.e., 7.5%). Moreover, the range of the 99% confidence interval indicates that there was less than a 1% chance of the true average opacity deviation being greater than 7%. These statistical results support the conclusion that the

accuracy of the DOCS to quantify the visible opacity of black smoke was equal to or greater than that established for the Method 9 procedure. Similarly, in evaluating the ability of certified smoke readers to measure the opacity of black smoke over the full opacity range, the average opacity deviation was estimated to be 7.45%. Although the average deviation was below the acceptable 7.5% error rate associated with the Method 9 procedure, the 99% confidence interval included deviations that were greater than 7.5%, a fact that suggests that there would be a high degree of uncertainty associated with the conclusion that the certified human readers could reliably maintain the minimum Method 9 accuracy requirement.

In contrast to black smoke, the field data indicated that over the full range of opacity (0–100%), neither the DOCS nor the certified human observers could measure the opacity of white plumes with the minimum Method 9 accuracy. Both opacity measurement approaches yielded average opacity deviations that were significantly greater than the acceptable margin of error associated with Method 9. The failure of the DOCS to accurately measure white plumes over the full range of opacity stems primarily from the inability of the proprietary software to exclude the effects of shadows, which were characteristic of high-opacity white plumes (i.e., those having opacities of greater than 60%).

Despite the failure of the DOCS to meet the minimum Method 9 accuracy requirements during opacity measurements of white smoke plumes, when the statistical procedures were applied to a limited range of visible opacity, the DOCS not only met the minimum accuracy requirements but was found to have significantly greater accuracy than Method 9–certified human observers. For example, over the 0–60% opacity range for white smoke, the average opacity deviation of DOCS was estimated to

Table 3. Statistical data summary of Weber County, UT, smoke school DOCS evaluation.

Color of Smoke	Opacity Measurement Approach	Opacity Range (%)	Average Deviation (%)	Number of Samples	99% CI ^a
Black	DOCS	0–100	6.58	2357	6.1–7
Black	Certified observers	0–100	7.45	280	6–8.8
Black	DOCS	0–60	5.70	1972	5.3–6.1
Black	Certified observers	0–60	5.82	225	4.5–7.1
Black	DOCS	0–40	5.44	1759	5–5.9
Black	Certified observers	0–40	4.77	194	3.5–6.1
White	DOCS	0–100	10.08	2410	9.5–10.7
White	Certified observers	0–100	8.55	282	7.1–10
White	DOCS	0–60	6.70	1900	6.2–7.2
White	Certified observers	0–60	8.17	224	6.6–9.8
White	DOCS	0–40	5.90	1689	5.4–6.4
White	Certified observers	0–40	7.39	199	5.7–9

^aCI = confidence interval.

be 6.7% with a 99% confidence interval that ranged from 6.2 to 7.2%. These data indicate that, if the opacity of the white plume were equal to or less than 60%, the DOCS accuracy would exceed the minimum level required for demonstrating equivalency to Method 9. Furthermore, the 99% confidence interval indicates that there was less than a 1% chance of the true average deviation being greater than 7.2. These statistical results support the conclusion that the accuracy of the DOCS in measuring the opacity of white smoke over the range of 0–60% opacity was significantly greater than that established for Method 9. In contrast to the ability of the DOCS to attain the Method 9 accuracy requirements when its application was limited to the 0–60% opacity range for white plumes, opacity results reported by the certified human observers indicated that the human observers exceeded the allowed Method 9 error rate. For example, over the limited opacity range of 0–60%, the average opacity deviation associated with certified smoke readers was estimated to be 8.17% with a 99% confidence interval that ranged from 6.6 to 9.8%. Finally, it should be noted that, over the range of visible opacity levels typically established for regulated air sources (i.e., 0–40% opacity), the accuracy of the DOCS was significantly greater than the level required to demonstrate equivalency to Method 9, regardless of the color of the plume (see Table 3).

To more fully characterize the technical limitations of the DOCS in quantifying visible emissions, the effect of camera position on opacity measurement was evaluated. As illustrated in Figure 2, two of the DOCS cameras were placed directly in line between the sun and the smoke stack (designated as camera positions C2 and C3), while the two remaining DOCS cameras were placed at the extreme azimuth angle permissible for taking valid Method 9 opacity measurements (identified as camera

positions C1 and C4). Table 4 summarizes the statistical results obtained from the DOCS and certified human observer comparison, which was evaluated at the various digital camera/observer positions.

Comparison of the opacity deviations as a function of the camera/human observer position indicated that, as long as the visible emissions were observed from a distance of at least three stack heights from the emission source with the sun contained within the allowable 140° sector as prescribed by the Method 9 protocol, camera position did not impact the accuracy of the DOCS in quantifying opacity. For example, in estimating the visible emissions associated with black smoke, the most accurate readings for the DOCS were taken from the C1 position (e.g., average opacity deviation 5.4%), while for the certified human reader, the most accurate readings were recorded from positions C2 and C3 (average opacity deviation 6.38%). Conversely, for white smoke, the most accurate readings for both the DOCS and the certified human readers were from C1, where the average deviations were 6.28 and 8.77%, respectively. These data suggested that the specific positioning criteria prescribed for certified human observers when taking valid Method 9 opacity readings could be adopted by the DOCS field protocol without any adverse effects on the accuracy of the opacity measurement.

CONCLUSIONS

The field results obtained in the present study clearly demonstrate that the DOCS has the potential of satisfying the technical and quality performance standards to qualify as an alternative to Method 9. The statistical accuracy of the DOCS in quantifying the opacity of black plumes was found to be significantly greater than the minimum level established for measuring visible opacity using

Table 4. Effect of digital camera position on the accuracy of the DOCS measurement.^a

Color of Smoke	Opacity Measurement Approach	Camera Position	Opacity Range (%)	Average Deviation (%)	Number of Samples	99% CI ^b
Black	DOCS	C1	0–100	5.40	603	4.7–6.1
Black	DOCS	C2, C3	0–100	6.71	939	5.9–7.6
Black	DOCS	C4	0–100	7.31	815	6.6–8.1
Black	Certified observers	C1	0–100	9.06	106	6.4–11.7
Black	Certified observers	C2, C3	0–100	6.38	149	4.7–8.1
Black	Certified observers	C4	0–100	7	25	3.4–10.6
White	DOCS	C1	0–100	8.77	545	7.5–10
White	DOCS	C2, C3	0–100	10.63	1176	9.7–11.6
White	DOCS	C4	0–100	10.20	689	9.1–11.3
White	Certified observers	C1	0–100	6.28	98	4.6–7.9
White	Certified observers	C2, C3	0–100	7.28	112	5.6–9
White	Certified observers	C4	0–100	13.61	72	9.7–17.5

^aSee Figure 2 for exact camera/observer location; ^bCI = confidence interval.

Method 9. For white smoke, the accuracy of the DOCS is statistically less than the Method 9 error rate only when the actual (i.e., true) opacity was limited to the range of 0–60%. The technical reason cited by the developers of the DOCS for its inability to accurately quantify the opacity of dense white plumes is the effect of shadows, which are often associated with these types of emissions. An extensive presence of shadows within the digital image decreases the ability of the DOCS proprietary software to effectively differentiate between visible emissions and background, which can result in significantly reducing the accuracy of the opacity measurement.

From a regulatory standpoint, the inability of the DOCS to accurately measure the opacity of dense white plumes means that the technology, in its present design, is incapable of successfully passing an EPA-approved smoke school. Despite this limitation, for those opacity ranges typically included in regulatory permits (0–40%), the accuracy of the DOCS was found to exceed the minimum requirements established for quantifying opacity using Method 9 regardless of plume color. The effect of camera position on the DOCS accuracy in measuring plume opacity was found to be negligible, provided that the digital photographs were taken from locations that were consistent with the human observer positioning criteria specified by Method 9. Moreover, like Method 9, the DOCS cannot reliably quantify opacity levels of visible emissions when the plume is subject to folding or twisting or is obstructed by physical objects.

Finally, in developing the scope of the DOCS experimental field design, it was recognized that, because of its dependency on electronically powered optical equipment, the response of the DOCS could vary significantly depending on climatic conditions. In other words, temperature, humidity, and other environmental factors could potentially affect the accuracy of the DOCS in quantifying visible opacity. Therefore, the present field results only reflect the performance of the DOCS under low humidity and high visibility climatic conditions, that is, those climates typically encountered in high mountain deserts. It is anticipated that analysis of the DOCS performance at EPA-approved smoke schools conducted in humid climates or in locations with a high degree of cloud overcast will provide important field results that are necessary to more fully describe the impact of climatic conditions on the technology's ability to quantify visible emissions.

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About the Authors

Dr. Michael J. McFarland is an associate professor and Spencer H. Terry is a graduate research assistant in the Department of Civil and Environmental Engineering at Utah State University in Logan, UT. Dr. Daniel A. Stone is senior environmental scientist and Steven L. Rasmussen is air compliance program manager in the environmental management directorate at Hill Air Force Base in Ogden, UT. Capt. Michael J. Calidonna is a manager of environmental technology demonstration with the U.S. Air Force's Engineering and Services Research Laboratory at Tyndall Air Force Base in Panama City, Florida. Address correspondence to: Dr. Michael J. McFarland, Utah State University, 130 South 1000 East, River Heights, UT 84321; phone: (435) 753-3608; fax: (435) 753-4597; e-mail: farlandm@msn.com.